CHAPTER - VI

METAMORPHISM

The present chapter incorporates a discussion of the metamorphism suffered by the rocks of the area. The various lithologic units of the Jakhri and the Rampur formations have been effected by polyphased deformation and metamorphism, thus, the original composition of the parent rocks shows marked changes due to reconstitution and recrystallisation as a result of which it is rather difficult to trace a logical sequence of the changes that occurred in their mineral assemblages. However, an attempt has been made, based on detailed petrological and geochemical studies, to decipher the metamorphic history of the area. The study further helps in identifying the parent rock composition of the lithologic units of the area as well as changes brought in them during various episodes of metamorphism vis-a-vis deformation. The mineral assemblage and fabric of a previous episode were changed or probably destroyed by subsequent phases of metamorphism. However, some textural and/or mineral relics disclose the probable nature of earlier metamorphic episodes.

Before discussing about the metamorphic facies and zones in the Rampur area, it is proposed to present a brief
survey of the various concepts proposed from time to time and being used in classifying the metamorphic rocks.

METAMORPHIC ZONES AND GRADES:

Iyell (1883) introduced the term 'metamorphism' in geological literature and since then various theories and hypotheses have been put forward to define 'metamorphism' and postulate the physico-chemical conditions required for different kinds of metamorphism.

The depth of burial as a cause of different pressure and temperature conditions, and consequent changes in mineral assemblage, had long been realised (Williams, 1889; Becke, 1904; Van Hise, 1904; Sederholm, 1907; Grubenmann, 1910; Grubenmann and Niggli, 1924; Junge and Roques, 1938; Misch, 1949). Accordingly, three different zones, i.e., (a) the upper or epizone, (b) the middle or mesozone and (c) the lower or katazone, characterised by progressive increase of temperature and pressure have been recognised with the increase in the depth.

Considering the present tectonic set up of the rocks in the study area, where the older and more metamorphosed rocks of Jakhri Formation have been thrust over the younger and comparatively less metamorphosed rocks of Rampur
Formation, the depth zone concept as such cannot be applied unless the rocks are re-arranged in their actual stratigraphic order. However, the fabric and mineral assemblages of these rocks suggest that the Jakhri rocks have suffered a mesograde metamorphism at deeper level while the Rampurs have undergone 'epigrade' to mesograde metamorphism at shallower depth.

Barrow (1893, 1912), while working on the Dalradian rocks of Scottish Highlands, put forward the hypothesis of progressive zones of metamorphism by selecting isochemical lithologic units and correlating them with increasing temperature and pressure. He proved that the zones of progressive regional metamorphism can be recognised on the basis of first appearance of certain index minerals in isochemical lithologic units. The idea was further developed by Tilley (1925) and Kennedy (1949) and others. Accordingly, zones of chlorite, biotite, almandine, staurolite, kyanite and sillimanite have been recognised in many metamorphic terrains. Since metamorphism has implications of both space and time, any generalisation about this sequence is not possible. Different types of metamorphism have been recognised in different metamorphic belts and in different geological times within the same belt (Miyashiro, 1961; Johnson, 1963; Hietanen, 1967; Zwart, 1967).
On account of the fact that the present area has suffered polymetamorphism, structural disturbances causing repetitions due to folding and inversion, widespread retrogression (and occurrence of secondary chlorite with garnet and biotite at higher grades) it is difficult to apply Barrow's concept of zones in its true sense. As such, mapping of zonal boundaries has not been possible. Nevertheless, a broad zonal classification of rocks on the basis of presence of characteristic index minerals has been attempted. Similar attempts have been made in other Himalayan regions by Das (1966), Kumar (1971), Virdi (1971), Mehta (1972) and others.

Zones Represented by Rocks of Rampur Formation:

The metapsammites of the Rampur Formation are characterised by quartz, chlorite, muscovite and occasionally albite whose metamorphism corresponds to chlorite-mica zone.

Some varieties of greenschists contain biotite in addition to other minerals whereas other are characterised by the presence of chlorite, actinolite, tremolite and albite (Table 3.3). It is, therefore, not possible to assign these rocks to a grade higher than that of biotite zone.
Other metabasics - amphibolite - which occurs in quartzite of Rampur Formation as a sill-like body contain hornblende, oligoclase (An > 15%), diopside and epidote but lack in garnet. This imparts a transitional character to assemblage in the upper part of almandine (garnet) zone.

Zones Represented by the Rocks of Jakhri Formation:

The metapelites and metasemipelites which are characterised by the presence of quartz, muscovite, biotite, and garnet may be assigned the status of almandine zone.

METAMORPHIC FACIES:

The zonal concept, as proposed by the earlier workers, is mainly based on physical conditions, namely, temperature and pressure. It has also been realised that chemical composition of the original rock is equally an important factor in the development of the mineral under a particular environment (Goldschmidt, 1911; Eskola, 1914, 1915; Read, 1948). This understanding led to the development of facies concept. Goldschmidt (1911), on the basis of his work in Oslo region of Norway, concluded that for a given chemical composition under the same P-T conditions, the resulting mineral assemblage is always the same and relatively simple. Becke (1913), while working in Austrian Alps, believed that
Eskola (1914, 1915), while discussing the contact metamorphic effects of Precambrian granites in the Orjjarvi region of Norway, came to a similar conclusion as that of Goldschmidt. However, there are some striking differences in the mineral paragenetic sequence in the above two areas, in spite of the fact that the same wide range of chemical compositions are represented. Such differences are attributed to the differences in the physical conditions during metamorphism (Eskola, 1914). Thus, Eskola (1914) defined a metamorphic facies as the one that includes rock of any chemical composition and hence widely varying mineralogical composition, which have reached a chemical equilibrium during metamorphism under a particular set of physical conditions.

Eskola (1939) developed the concept of metamorphic mineral facies and stated that mineral facies comprises all the rocks that have originated under temperature and pressure conditions so similar that a definite chemical composition has resulted in the same set of minerals quite regardless of their mode of crystallisation whether from a magma or aqueous solution or gas and whether by direct crystallization or by gradual change of earlier minerals (metamorphic crystallisation).
On the basis of mineralogical criteria, Eskola (1920) defined five facies. He (1939) later revised his original classification and added three more facies (Table 6.1).

Table 6.1
Correlation of facies with pressure and temperature (After Eskola, 1939).

<table>
<thead>
<tr>
<th>Pressure increasing</th>
<th>Temperature increasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development of zeolites in igneous rocks</td>
<td></td>
</tr>
<tr>
<td>Greenschist facies</td>
<td>Epidote-amphibolite facies</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Glaucophane schist facies</td>
<td>Eclogite facies</td>
</tr>
</tbody>
</table>

The scope of metamorphic facies developed by Eskola (1920) was expanded by Turner (1948), Fyfe, Turner and Verhoogen (1958), Turner and Verhoogen (1960). As a result of this, the number of main metamorphic facies was
increased and subfacies were introduced. Turner (1968) has distinguished eleven facies and some additional transitional facies whereas Hietanen (1967) has distinguished thirteen facies in all. Some authors favour the idea of subfacies (Winkler, 1967; Hietanen, 1967, 1968), whereas the idea of subfacies does not find favour with others (Chapman, 1939; Billings, 1937; Lambert, 1965). The facies was, therefore, redefined by Fyfe and Turner (1966) as a set of mineral assemblage repeatedly associated with one another in space and time such that there is a constant and therefore a predictable relation between the mineral composition and chemical composition. They advocated the restricted use of subfacies.

Turner (1968) proposed the following metamorphic facies arranged arbitrarily according to the pressure:

A. Facies of Low Pressures
   1. Albite-epidote-hornfels facies
   2. Hornblende-hornfels facies
   3. Pyroxene-hornfels facies
   4. Sanidinite facies

B. Facies of Medium to High Pressure
   5. Zeolite facies
   6. Prehnite-pumpeyellite-metagraywacke facies
7. Greenschist facies
8. Amphibolite facies
9. Granulite facies

C. Facies of Very High Pressure
10. Glaucophane-lawsonite facies
11. Eclogite facies

Figures 6,1a, b show P-T diagram with possible stability fields of metamorphic facies and the tentative correlation between facies, temperature and pressure.

Recent researches in metamorphic petrology has led Miyashiro (1961), Zwart (1963) and Hietanen (1967) to visualise that the mineral assemblage developed in the Scottish Highlands (Farrow, 1893) cannot be generalised. Different sequences of mineral assemblages have been recorded from different regions which characterise the type of metamorphism in a particular belt. According to Miyashiro (1961), each metamorphic terrain is characterised by a certain facies series. The following five types of metamorphism (or facies series) on the basis of the operating rock-pressures have been recognised:

1) Andalusite-sillimanite type (Abukuma type of Miyashiro, 1961; Japan type of Hietanen, 1967)
2) Low pressure intermediate group (Buchan type of Read, 1952; Pyrenean type of Zwart, 1963)

3) Kyanite-sillimanite type (Barrovian type - Hietanen, 1967; Winkler, 1967)

4) High pressure intermediate group (similar to number 3, but with glaucophane)


In the area under investigation, the mineral composition, textural and mutual relationship of different minerals in the rocks reveal that they have been repeatedly metamorphosed. The rocks of the area represent the end phase
of a long metamorphic history though the effects of the earlier episodes are discernible. It has been attempted here to classify the rocks according to their metamorphic characters as well as on the basis of the observed mineral assemblages and to assign them to different metamorphic facies.

Studies of mineral assemblages, their paragenesis and fabric data of the minerals in the rocks of the Rampur and Jakhri formations reveal that these rocks can be assigned to the following metamorphic facies:

i) Greenschist facies

ii) Greenschist-amphibolite transitional facies

iii) Amphibolite facies

The characteristic mineral assemblages and the P-T conditions for these facies are discussed in the following pages. The above three metamorphic facies have been grouped under the 'Harrowian type' or the kyanite-sillimanite type series (Fig. 6.1a) (Miyashiro, 1961; Hietanen, 1967, Winkler, 1967).

Table 6.2 shows the stability range of different minerals in Jakhri and Rampur metamorphites during different metamorphic facies.
TEMPERATURE IN DEGREES CENTIGRADE

(a) P-T Diagram showing possible stability fields of metamorphic facies

(b) Schematic relationship of metamorphic facies to temperature and pressure ($P = P_{H_2O}$)

(After Hietanen, 1967; After Frye & Turner, 1966, Vice-Turner, 1968)
Table 6.2: Stability ranges of minerals through various facies during metamorphism in the Rampur formation.

<table>
<thead>
<tr>
<th>Rock Formation</th>
<th>Metamorphic Zones</th>
<th>greenschist facies</th>
<th>Transitional Facies</th>
<th>Amphibolite Facies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minerals</td>
<td>Chlorite zone</td>
<td>Biotite zone</td>
<td>Almandine zone</td>
</tr>
<tr>
<td>Metamorphic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic</td>
<td>Pyroxene</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock</td>
<td>Flagiolazoise</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(oligoclase, An20-30)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metabasic</td>
<td>Actinolite-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocks</td>
<td>troctolite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metaplastic</td>
<td>Hornblende</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metaplastic</td>
<td>Epidote</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocks</td>
<td>Chlorite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metaplastic</td>
<td>Muscovite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocks</td>
<td>Biotite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metaplastic</td>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocks</td>
<td>Calcite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metaplastic</td>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocks</td>
<td>Chlorite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metaplastic</td>
<td>Muscovite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocks</td>
<td>Biotite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metaplastic</td>
<td>Flagiolazoise</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocks</td>
<td>(albite)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Green schist Facies:

The greenschist facies includes low grade regionally metamorphosed rocks which are completely recrystallised and well foliated and belong to the chlorite and biotite zones in the Barrovian zonal scheme (Turner, 1968). The characteristic minerals of greenschist facies include albite, white mica, biotite (restricted to higher grade), prochlorite, epidote minerals, dolomite (in silica deficient rocks) and tremolite-actinolite, talc antigonite in magnesian rocks.

In the present area, the metapsammites and most of the greenschists (metabasics) of Rampur Formation are of greenschist facies and are characterised by the following mineral assemblages:

Metapsammites:
Quartz-muscovite-biotite-albite-epidote

Metabasics:
Talc-tremolite-actinolite-albite-epidote
Tremolite-actinolite-albite-epidote+calcite
Actinolite-tremolite-albite-epidote
Chlorite-actinolite-biotite-albite-epidote+calcite

The formation of biotite (now chloritised) in the metapsammite of this facies may have been from the original
muscovite and chlorite.

The chlorite has been found to be stable along with biotite and muscovite and continues to do so till the temperature range of greenschist facies is exceeded. However, in the metapsammites, the presence of biotite indicates additional components in the original rocks in the form of pelitic and ferruginous impurities.

As regards the P-T conditions of metamorphism of the greenschist facies, there is no general agreement amongst the petrologists. Turner and Verhoogen (1960) have proposed 300°-350°C temperature and $P_{H_2O} = 3-8$ kb.

Winkler (1964) suggested that the lower limit of greenschist facies can be marked by the appearance of pyrophyllite and paragonite at about 400°C temperature and $P_{H_2O} = 2$ kb. Under these circumstances, it would be difficult to set precisely the lower limit of the P-T conditions for this facies.

However, the presence of some critical minerals and their transformation indicate that the temperature limit during this facies in the area could be near 350° ± 20°C when the reaction sets in.

Greenschist-Amphibolite Transitional Facies:

The rocks which have undergone metamorphism in the
middle and upper part of the almandine zone in the Harrobian zonal sequence are attributed to this facies. Presence of albite, oligoclase and almandine characterises this transitional facies.

In the present area, this facies is represented by the metasemipelite of the Jakhri Formation and also partly by metabasics of the Rampur Formation with the following mineral assemblage:

**Metasemipelites:**
Quartz-muscovite-biotite epidote-plagioclase+garnet

**Metabasics:**
Hornblende (bluish green) + orthoclase+oligoclase + andesine-actinolite-epidote + epidote + calcite

Chlorite which occurs in these rocks is secondary. In metabasics bluish green hornblende appears and is associated with felspars represented by oligoclase and orthoclase. However, with the increasing grade of metamorphism, the An-content goes on increasing and the plagioclase becomes more calcic in nature.

This facies formerly had been referred to as epidote-almandine-amphibolite facies (Eskola, 1939). Turner and Verhoogen (1960) classified this as a subfacies of almandine zone in the Harrobian zonal sequence are attributed to this facies.* Presence of albite, oligoclase and almandine characterises this transitional facies.

In the present area, this facies is represented by the metasemipelite of the Jakhri Formation and also partly by metabasics of the Rampur Formation with the following mineral assemblage:

**Metasemipelites:**
Quartz-muscovite-biotite epidote-plagioclase+garnet

**Metabasics:**
Hornblende (bluish green) + orthoclase+oligoclase + andesine-actinolite-epidote + epidote + calcite

Chlorite which occurs in these rocks is secondary. In metabasics bluish green hornblende appears and is associated with felspars represented by oligoclase and orthoclase. However, with the increasing grade of metamorphism, the An-content goes on increasing and the plagioclase becomes more calcic in nature.

This facies formerly had been referred to as epidote-almandine-amphibolite facies (Eskola, 1939). Turner and Verhoogen (1960) classified this as a subfacies of...
greenschist facies. Turner (1968), however, designated it as a transitional facies between the greenschist and amphibolite facies.

In the transitional facies, biotite becomes quite abundant and the almandine garnet appears for the first time to remain stable throughout the whole range of metamorphism. Almandine, however, becomes frequent in the amphibolite facies.

Considering the metasemipelitic and some metabasic assemblages of almandine zone in the area, it is evident that they represent the transitional characters and have been described as transitional facies assemblages following Turner (1968). Similar transitions in the upper part of the almandine zone have been observed in the Dalradian rocks of Scottish Highland (Wiseman, 1934; Williamson, 1953) in the Alpine schists of Southwestland, New Zealand (Evans, 1964; Crawford, 1966) and in the Sanbagawa schist belt of Japan (Banno, 1964).

Amphibolite Facies:

Amphibolite facies is the typical of mesograde metamorphism in orogenic belts and with increase in the grade of metamorphism beyond the almandine zone in the
Barrovian zonal sequence, the rocks enter amphibolite facies (Turner, 1968). Eskola (1939) defined the amphibolite facies to include the metamorphic paragenesis represented by hornblende and plagioclase (oligoclaseandesine or some more basic variety). Francis (1956), Fyfe, Turner and Verhoogen (1958), Turner and Verhoogen (1960) and Winkler (1967) designated it as almandine-amphibolite facies. Although almandine occurs in many amphibolites after which the facies was named yet amphibolite without almandine is quite common. Fyfe and Turner (1966) therefore reinstated its more popular name 'amphibolite facies' (Eskola, 1939) in place of the almandine-amphibolite facies. This facies is characterised by hornblende-plagioclase (>An20) assemblages in basic rock which may or may not contain almandine. According to Winkler (1967), appearance of staurolite and oligoclase (>An15) marks the onset of Rm facies. However, staurolite is quite restricted in its occurrence in nature because it requires special conditions for its formation. Hence the other criteria could also indicate whether or not the amphibolite facies conditions have been attained in a particular area.

In the Rampur area, the amphibolite facies is represented by the metapelites of the Jakhri Formation and amphibolites of the Rampur Formation. The metapelitic rocks are characterised by development of almandine garnet and
biotite. In spite of careful and detailed observation in this part of the area, the author could not observe staurolite in these rocks. The occurrence of staurolite in such rocks of the adjoining areas have been noted. The absence of staurolite from the rocks of the present area does not, however, disqualify these rocks to be assigned to the amphibolite facies. The characteristic mineral assemblages determined in the rocks of the study area are:

Metapelites:
Quartz-biotite-muscovite-oligoclase epidote-almandine-albite
Quartz-biotite-muscovite-oligoclase-potash felspar+almandine+epidote

Amphibolites:
Hornblende-plagioclase (An$_{20-30}$)+epidote-biotite+quartz

The ACF and AKF diagrams (Turner, 1968; Winkler, 1967) plotted from the analysed data of these rocks clearly depict the paragenesis of the metasediments (Fig. 6.2a,b) and the metabasics (Figs. 6.3 & 6.4).

Chemical analyses of metasediments show that they do not fall in staurolite (or alternatively chloritoid) field (Fig. 6.2a). Thus, neither staurolite nor chloritoid could have formed.
FIG. 6.2

a. AKF DIAGRAM FOR METASEDIMENTS OF THE AREA

b. ACF DIAGRAM FOR THE METASEDIMENTS OF THE AREA
FIG. 6.3 A’C F DIAGRAM FOR THE METABASICS OF THE AREA. Symbols same as in fig. 5.1
underlined assemblage is for greenschist facies (exclusively)
FIG. 6.4 - A'K F DIAGRAM FOR THE METABASICS OF THE AREA. Symbols same as in fig. 5.1. Underlined assemblage is for greenschist facies (exclusively).
The most common formation of staurolite in the metapelites is after chloritoid according to the following reaction:

\[ 9 \text{ chloritoid} \rightarrow 2 \text{ staurolite} + \text{quartz} + 5\text{FeO} + 8\text{H}_2\text{O} \]

(Hietanen, 1967)

Chloritoid + andalusite/kyanite \rightarrow Staurolite + quartz + H_2O

(Hoscheck, 1967a)

However, both Hietanen (1967) and Hoscheck (1967a) are of the opinion that in the absence of chloritoid, staurolite may also be formed by the alternative reactions as follows:

Muscovite + chlorite \rightarrow Staurolite + biotite + quartz + H_2O

(Hoscheck, 1967b)

Muscovite + chlorite + FeO \rightarrow Almandine + staurolite + biotite

3Muscovite + 4FeO \rightarrow 2Staurolite + 3K_2O + 10quartz + 5H_2O

(Hietanen, 1967)

Since chlorite and muscovite were very much available in the metapelites, it can be safely assumed that the conditions for the formation of staurolite by these reactions were still not realised although the conditions for
the development of amphibolite facies assemblage had already set in with the formation of oligoclase.

The development of almandine and biotite may be shown by the following reaction:

\[
2 \text{ Chlorite} + \text{ muscovite} + 4 \text{ FeO} \rightarrow 2 \text{ Quartz} + \text{ biotite} + \text{ almandine} + 8 \text{ H}_2\text{O}
\]

\[
\text{Chlorite} + 4 \text{ silica} \rightarrow 3 \text{ Almandine} + 8 \text{ H}_2\text{O}
\]

The amphibolite of the area shows a marked increase in minerals like epidote, and biotite. The plagioclase shows further increase in An-content and is now predominantly oligoclase or oligoclase-andesine (An\text{20}-30). It is evident from the extensive amount of epidote, being developed at the cost of plagioclase, that the plagioclase must have been originally more calcic. Epidote formed after hornblende in association with sphene and biotite is, in fact, subordinate in amount to that formed by the saussuritisation of plagioclase. A swarm of epidote crystals develop in clear area possibly by the following reaction:

\[
\begin{align*}
(1) & 3\text{CaAl}_2\text{Si}_2\text{O}_8 + \text{CaO} + \text{H}_2\text{O} \rightarrow 2\text{Ca}_2\text{Al}_3(\text{OH})(\text{SiO}_4)_3 \\
(2) & 4\text{CaAl}_2\text{Si}_2\text{O}_8 + \text{H}_2\text{O} \rightarrow 2\text{Ca}_2\text{Al}_3(\text{OH})(\text{SiO}_4)_3 + \text{Al}_2\text{O}_3 + 2\text{SiO}_2
\end{align*}
\]
If the original plagioclase were lime-rich, then Ca released by their destruction would participate in the reaction (1). If, however, no Ca was released or else simple hydration took place then the change is better explained by the reaction (2). Soda released from the plagioclase during the process may be incorporated in the amphibole lattice to contribute to its bluish tinge. Silica so released may form vermicular intergrowth with epidote as a part of this process.

Hornblende occurring in the amphibolites of the area is typical green hornblende which is characteristic of this facies. During transformation from the original pyroxene to hornblende, some relics of the former are found in the core of the latter which give valuable information as to their parentage (cf. Pande, 1949). In the present case, schiller structures characteristic of pyroxene are also observed in the core of some hornblende crystals. During the uralitisation of pyroxene, lime is liberated which forms sphene with available titanium. Further, retrogression from hornblende to biotite, epidote and sphene took place during the waning phases of temperature. Round drop-like aggregates of sphene having ilmenite in their core are considered to be characteristic of retrogressive changes in ortho-amphiboles (William, Turner and Gilbert, 1965).
Ramberg (1952) gives the following reaction for the development of epidote and biotite during the retrograde alteration of hornblende:

$$\text{Ca(Mg,Fe)}_3\text{Al}_4\text{Si}_6\text{O}_{22}(\text{OH})_2 \rightarrow \frac{3}{2}\text{K}_2\text{O} + x\text{SiO}_2 + \frac{1}{2}\text{H}_2\text{O} \rightarrow \text{K(Mg,Fe)}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2 + \text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH})$$

Regarding P-T conditions of amphibolite facies, Turner and Verhoogen (1960) suggested that the metamorphism in the almandine-amphibolite facies covers a temperature range of 530°C-750°C and water pressure normally between 4 to 8 kb. Turner (1968) favours a temperature upward of 500°C at water pressure of a few kb for the development of staurolite-mica-quartz and staurolite-chloritoid-mica-quartz assemblages which mark the beginning of amphibolite facies. Winkler (1967) suggests that the appearance of staurolite is one of the most reliable indications of the beginning of the amphibolite facies.

It has been commonly suggested that the staurolite is formed at the expense of chloritoid. Hoschek and Winkler (1968) and Hoschek (1967a) obtained staurolite at 545°C ± 15°C temperature at $P_{\text{H}_2\text{O}} = 4\text{-}7$ kb. In the absence of chloritoid staurolite can also be obtained from muscovite and chlorite (Hoschek, 1967b; Hietanen, 1967). Hoschek (1967b)
obtained staurolite in this way at $540^\circ C \pm 15^\circ C$ at $P_{H_2O} = 4$ kb and at $560^\circ C \pm 15^\circ C$ at $P_{H_2O} = 7$ kb. Based on these results, Winkler (1967) suggested the onset of amphibolite facies at $550^\circ C$. Turner and Verhoogen (1960), however, placed the greenschist-amphibolite facies boundary at $500^\circ C$.

Since the composition of metapelites of the present area was not suitable for the formation of chloritoid and subsequently of staurolite, the absence of staurolite cannot be taken as indicative of non-achievement of amphibolite facies conditions in the area. However, the reaction between muscovite, chlorite, and iron ore could have been a possibility. Failure of such a reaction taking place indicates that the temperature was still short of $540^\circ C \pm 15^\circ C$. The lower limit of this facies as far as the Rampur area is concerned, therefore, can be placed at some temperature below $540^\circ C$ and possibly around $500^\circ C-520^\circ C$ which is similar to that fixed by Engel and Engel (1958, 1960) for the Adirondack paragneisses.

It will not be out of place to point out that the rocks of the area suffered repeated metamorphism during the Himalayan orogeny. The facies which they indicate now is actually the sum total of the result of all the metamorphic events.
METAMORPHIC HISTORY:

Within the life span of a metamorphic belt one or more major periods of metamorphism occur, during each of which a succession of phases of deformation and recrystallisation develop and each of these major metamorphic events can be subdivided into metamorphic episodes (Sutton, 1965).

The study of structure as well as petrography coupled with metamorphic facies and zones revealed that the rocks of the present area have undergone polyphase metamorphism. Similar opinions have also been expressed by Pande (1956-57), Pande, Powar and Das (1963), Das and Pande (1964-65), Kanwar (1965), Das (1966), Powar (1966), Kumar (1968), Bisaria (1970), Virdi (1971), Kumar (1971), Mahajan (1971), Kumar (1972), Mehta (1972), Kapila (1975), Singh (1977) and others who have worked either in Kumaon or Punjab Himalayas.

Early Metamorphism (?):

The question whether the rocks of the area suffered any metamorphism prior to the Himalayan orogeny is difficult to decide. Pilgrim and West (1928) observed that Jutoghs (in Simla region) had undergone recumbent folding and high grade regional metamorphism prior to the deposition of the Chails (Algonkian ?). Pande (1975) is of the opinion that the rocks of the inner schistose belt may have suffered
metamorphism prior to Himalayan orogeny but the imprints of which have been superimposed and obliterated by the Himalayan events. Fuchs (1967) considered Chails to be Devonian in age and their metamorphism as Alpidic and not Precambrian. Frank and Fuchs (1970) are divided on this issue. Naha and Ray (1970) have disagreed with the contention of Pilgrim and West (1928) on the very fact of the presence of recumbent folding in Chails. It may be true that the earlier orogenies like the Caledonian and Hercynian have affected and the structures could have survived after undergoing polyphased tectonism and metamorphism during the Himalayan orogeny; it is just a matter of conjecture.

The effect of these metamorphic events must have been partly or completely obliterated as a result of the later metamorphism. According to Kumar (1968), the effect of early episode is confined only to the allochthon. This episode resulted in the development of minerals like chlorite, sericite and biotite.

The history of metamorphism deciphered in the rocks of the Rampur area could be divided into five episodes (Table 6.3).

**Episode I - Load Metamorphism:**

The effect of this episode of metamorphism is
<table>
<thead>
<tr>
<th>Metamorphic episodes</th>
<th>Jakbi Formation: Metapeliteic and metapsammitic rocks</th>
<th>Metabasic rocks</th>
<th>Rampur Formation: Metapsammitic rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early metamorphism ?</td>
<td>Chlorite</td>
<td>Olivine (?)</td>
<td>Quartz (with argillaceous cementing material)</td>
</tr>
<tr>
<td></td>
<td>Sericite</td>
<td>Pyroxene</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quartz</td>
<td>Calcic plagioclase</td>
<td></td>
</tr>
<tr>
<td><strong>Episode I</strong></td>
<td>Quartz-I (sericite)</td>
<td>Pyroxene, less calcic plagioclase</td>
<td></td>
</tr>
<tr>
<td>Load metamorphism</td>
<td>Biotite (?)</td>
<td>Amphiboles</td>
<td></td>
</tr>
<tr>
<td><strong>Episode II</strong></td>
<td>Quartz-I and II</td>
<td>Uralitization of pyroxene</td>
<td>Quartz</td>
</tr>
<tr>
<td>Progressive regional</td>
<td>Biotite-I</td>
<td>and decalcification of</td>
<td>Muscovite</td>
</tr>
<tr>
<td>metamorphism</td>
<td>Garnet-I</td>
<td>plagioclase</td>
<td>Biotite (local)</td>
</tr>
<tr>
<td></td>
<td>Muscovite-I</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chlorite-I</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Episode III</strong></td>
<td>Degeneration of biotite and garnet to chlorite</td>
<td>Uralitization of pyroxene</td>
<td>Quartz</td>
</tr>
<tr>
<td>Retrograde metamorphism</td>
<td>Ferrimuscovite</td>
<td>and decomposition of</td>
<td>Muscovite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Muscovite plagioclase to less calcic</td>
<td>Biotite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>plagioclase and epidote</td>
<td>Chlorite</td>
</tr>
<tr>
<td><strong>Episode IV</strong></td>
<td>Quartz-I and II</td>
<td>Green hornblende</td>
<td></td>
</tr>
<tr>
<td>Second Phase of regional</td>
<td>Biotite-I and II</td>
<td>Actinolite</td>
<td></td>
</tr>
<tr>
<td>metamorphism</td>
<td>Garnet-I and II</td>
<td>oligoclasme</td>
<td>-do-</td>
</tr>
<tr>
<td>(geothermal)</td>
<td>Muscovite-I and II</td>
<td>Biotite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Formation of felspars</td>
<td>Epidote</td>
<td></td>
</tr>
<tr>
<td><strong>Episode V</strong></td>
<td>Quartz-I and II</td>
<td>Hornblende, Actinolite</td>
<td>Quartz</td>
</tr>
<tr>
<td>Late retrogressive metamorphism</td>
<td>Biotite-I and II</td>
<td>Quartz</td>
<td>Muscovite</td>
</tr>
<tr>
<td></td>
<td>Garnet-I and II</td>
<td>Plagioclase, oligoclasme</td>
<td>Biotite</td>
</tr>
<tr>
<td></td>
<td>Muscovite-I and II</td>
<td>Epidote</td>
<td>Chlorite</td>
</tr>
<tr>
<td></td>
<td>Chlorite-I,II &amp; III</td>
<td>Biotite, Chlorite</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Formation of sphene, ilmenite &amp; opaques</td>
<td></td>
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</tbody>
</table>
recognisable in both the tectonic units (Unit A and Unit B). The rocks which were being deposited at the base of the southern geosyncline (Pandé, 1967) were overlain by the huge pile of sediments deposited during the Palaeozoic and Mesozoic Eras. Due to the superimposed load, the rocks which were at deeper levels underwent static deformation prior to the Himalayan orogeny (Pande and Saxena, 1968). With the increasing load of superincumbent material, the floor of the southern geosyncline was gradually sinking accompanied by deep burial along with a rise in temperature. The rocks suffered load metamorphism and the chemical reconstitution under vertically directed load at temperature conditioned by the depth (Milch, 1894; Dawson, 1904; Daly, 1912, 1915, 1917; Mahajan and Pande, 1974; Pande, 1975). Similar types of metamorphism have been described as geosynclinal metamorphism (Misch, 1949) or burial metamorphism (Winkler, 1967).

This episode resulted in recrystallisation giving rise to bedding schistosity in the Jakhri Formation (Unit A) and bedding cleavage in the Rampur Formation (Unit B) which was at higher level. Recrystallisation due to rise in temperature led to the formation of new minerals such as chlorite, muscovite, biotite in pelitic and semipelitic rocks and less calcic plagioclase as well as amphiboles in
basic rocks. The $S_1$-planes became the potential slip planes for the ultimate development of the main schistosity and slaty cleavage ($S_2$) under directed pressure during succeeding regional metamorphism and deformation. The maximum effect of this episode was witnessed by rocks of Unit A.

It appears that this metamorphism took place probably prior to folding in the area. The effects of Episode-I are still traceable in the rocks although due to subsequent effects of progressive regional metamorphism (Episode-II) accompanied by folding phase $D_1$ (Table 4.5), the imprints of this event have been partially or completely obliterated or rendered too obscure to be recognised.

Episode II - Progressive Regional Metamorphism:

The load metamorphism gradually changed to progressive metamorphism with increasing lateral forces during the Cretaceous-Eocene period which was contemporaneous to the major deformational phase $D_1$. It is difficult to distinguish the effect of load metamorphism from those of regional metamorphism. Possibly, with the rise in temperature, folding movements and introduction of chemically active fluids in the system, the load metamorphism passed gradually into regional metamorphism as a continuous process. The dividing line is arbitrary and is governed by the
fluctuation in temperature and amount of circulating solutions.

During this episode, flaky minerals developed in the rocks of the area. These flaky minerals together with quartz were recrystallised and mark the main schistosity or cleavage ($S_2$) in the rocks of Unit A and Unit B respectively, which is parallel or subparallel to the axial planes of first folds ($F_1$) (Chapter V). The regional metamorphism suffered by the rocks of the area was synkinematic or syntectonic in nature as exhibited by the syntectonic growth of these minerals.

In the rocks of Unit A (Jakhri Formation) chlorite, sericite and quartz recrystallised and reacted to form chlorite I, muscovite I, biotite I and garnet I. Original clastic quartz I recrystallised to form quartz II. The garnet I grew in size by incorporating matrix material and exhibited sigmoidal, spiral and other complex patterns of inclusions. Though views regarding formation of these inclusions differ yet almost all the authors agree that these features are characteristic of growth during deformation, which in the present case was syntectonic with respect to deformational phase $D_1$. 
The original pyroxene in the basic rocks of Unit B (Rampur Formation) were uralitised, calcic plagioclase saussuritised and epidotised.

Since the metabasics share the same principal foliation ($S_2$) as other rocks, it is evident that they also suffered metamorphism during this episode. It indicates that they are in conformity with the general nature of the evolution of orogenic belts (Hess, 1938, 1955; Read, 1957).

In the metapsammitic rocks, the quartz grains were recrystallised and some flaky minerals were formed due to the recrystallisation of clay impurities.

**Episode III - Retrograde Metamorphism:**

The second episode (progressive regional metamorphism) was followed by an intermittent phase of deformation during which the temperature declined and stress was released along the weak planes. This resulted in the retrogression or diaphoresis (Becke, 1909) of minerals formed during episode II. Biotite and garnet altered to chlorite along with release of iron oxides etc. which maintain the textural continuity along $S_2$.

In the metabasics, the original pyroxene and calcic...
plagioclase were further degenerated to hornblende, biotite, epidote and less calcic plagioclase.

Episode IV - Second Phase of Progressive Metamorphism:

Progressive regional metamorphism was revived due to increase in temperature. Overall grade of metamorphism during this phase was higher because of higher temperature and correspondingly lower stresses in comparison to episode II. The characteristic assemblages of respective metamorphic facies were formed after the completion of this episode but prior to the final retrogression (Hietanen, 1968).

The earlier minerals were recrystallised and new-mineralisation took place by their reactions. During this episode, temperature and circulating fluids played an important role. The porphyroblastic biotite II, muscovite II and garnet II developed during this stage and exhibit post tectonic or post kinematic relationship with the fabric of the minerals formed in episode II. Under the conditions of high temperature, the recrystallisation of rocks at depth is inevitable. The migration of alkalies along the privileged paths resulted in the formation of felspars as observed in the felspathic mica schist of the Jakhri Formation.

The metabasics were completely recrystallised to hornblende-oligoclase-epidote assemblage at this stage. Some
crystals of hornblende developed large piokiloblastic habit.

Episode V - Late Retrogressive Metamorphism:

The last episode in the history of metamorphism in the present area was of retrogressive nature. This was probably linked with the thrusting of Unit A over the Unit B and adjustment along the dislocation planes.

During this episode, the temperature was progressively declining but shearing stresses associated with thrusting movements became violent, resulting in both textural and mineralogical degeneration of rocks. The rocks along the thrust zone have been crushed and mylonitised.

Mineralogical changes include degeneration of garnet, biotite, hornblende, feldspars and other minerals. Chlorites formed from biotite I and biotite II maintain textural relationship.

In the metabasics, pyroxenes were completely uralitised. Hornblende was further degenerated to biotite, sphene, epidote and ilmenite which in turn were further changed to chlorite and leucoxene. Plagioclase was further epidotized and saussuritized.
The cataclastic texture is pronounced in the rocks along the zone of thrusting where the felspars and quartz porphyroclasts occur in pulverised and crushed groundmass and sometimes they are fractured with their twin-lamellae bent. Garnet II was also fractured.

Becke (1909) has proposed the term 'diapthoresis' for such reverse metamorphism. Schwartz and Todd (1941) have emphasized the availability of water for such retrogressive phenomenon which is evident from the change of garnet and biotite to chlorite. Turner and Verhoogen (1960) proposed that retrogression triggered by stresses may become widespread if sufficient water is available. It is, therefore, evident that in the Rampur area the retrogressive metamorphism occurred under the conditions of falling temperature and extensive shearing stress in the presence of water.